

Pressure and Temperature Sensitive Paint Field System

*Danny R. Sprinkle, Clifford J. Obara, Tahani R. Amer, Nettie D. Faulcon, Michael T. Carmine,
Cecil G. Burkett, and Daniel W. Pritchard
Langley Research Center, Hampton, Virginia*

*Donald M. Oglesby
Swales Aerospace, Hampton, Virginia*

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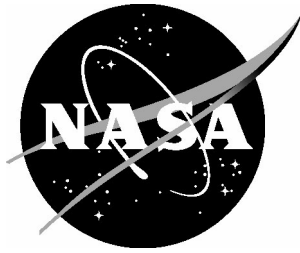
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*Donald M. Oglesby
Swales Aerospace, Hampton, Virginia*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Abstract

This report documents the Pressure and Temperature Sensitive Paint Field System that is used to provide global surface pressure and temperature measurements on models tested in Langley wind tunnels. The system was developed and is maintained by Global Surface Measurements Team personnel of the Data Acquisition and Information Management Branch in the Research Facilities Services Competency. Descriptions of the system hardware and software are presented and operational procedures are detailed.

Introduction

When exposed to light of an appropriate wavelength, pressure sensitive paint (PSP) luminesces with an intensity inversely proportional to the partial pressure of oxygen of its environment. When applied to a wind tunnel model PSP can provide a picture of the varying pressures over the model surface. An image is acquired with tunnel wind off, another image is acquired with wind on, and these images are ratioed and calibrated against model surface static pressure tap data to render a false-color image of pressure.¹ Temperature sensitive paint (TSP) similarly responds to a change in temperature.

PSP/TSP have been used at Langley in various wind tunnels since the 1990's.² A complement of hardware, software, and operational procedures used by the Global Surface Measurements Team over the years has thus evolved into a PSP/TSP Field System. It is the purpose of this report to document the hardware, software, and operational procedures of the PSP/TSP Field System so that current and future users of the system may be provided with a standard methodology of use. This report lists and describes the system hardware and details the operational procedures including test documentation with examples.

Field System Hardware

Camera Systems

Several scientific grade camera systems are available for specific applications. A description of the camera systems is provided in Table 1.

¹ Danny R. Sprinkle, Clifford J. Obara, Tahani R. Amer, Bradley D. Leighty, Michael T. Carmine, Cecil G. Burkett, and Bradley S. Sealey: *Langley 16-Ft. Transonic Tunnel Pressure Sensitive Paint System*, NASA/TM-2001-211017, June 2001.

² T. R. Amer.; C. Obara.; W. Goodman; B. Sealey; C. Burkett; and T. Carmine: Pressure Sensitive Paint Measurements in NASA-Langley Wind Tunnels. *Proceedings of the 45th International Instrumentation Symposium*, Instrument Society of America, 1999, pp. 325-334.

Table 1. PSP/TSP Field System Cameras

CAMERA	BITS	ARRAY	FEATURES
Photometrics Sensys	12	768 x 512	Back-illuminated Thermoelectric cooling
Photometrics CH-250	14	512 x 512	Back-illuminated Liquid cooled
Photometrics CH-350	16	512 x 512	Back-illuminated Liquid cooled
Princeton CCD-512SB	16	512 x 512	Back-illuminated Liquid cooled
PixelVision Custom	16	1k x 1k	Back-illuminated Thermoelectric cooling
Silicon Mountain Design 1M60	12	1k x 1k	Back-illuminated Fast framing (110 fps)

Computers

Several computers are used to operate the field system and conduct the post-test image processing. These include Microsoft Windows based personal computers for image acquisition and Unix-based workstations and Linux-based personal computers for image processing. Image data are backed up on removable media.

Lighting Systems

Several lighting systems are on hand to illuminate models of various sizes and from various distances:

1. 18 ELC-250 UV lamps and associated power supplies.
2. Several small in-house assembled UV lights.
3. 18 LED lamp assemblies.

Accessories

Numerous lenses and filters are kept on hand as well as painting supplies and mounting hardware for cameras and lights. A coordinate measurement system is used to measure model geometries.



Figure 1. PSP/TSP Field System components (clockwise from top-left): camera system and PC; UV lamp test set-up; image processing stations; LED lamp test set-up.

Field Test Documentation

All phases of a field test should be documented beginning with a Test Support Request Form that will include basic information about the test. A Test Requirements document will include a formal outline of the test requirements based on the Test Support Request Form. A Test Plan will detail steps necessary to fulfill the test requirements. The Test Log will record on a daily basis useful information concerning the test. Examples of each of these documents are given in the following sections. These documents are maintained as per ISO 9000 procedures on a limited-access website. Test customers may request access to the site.

In addition to textual documentation it is desirable to photo-document the tunnel test section and the test model using a digital camera. Special attention should be given to the test section geometry as

regards camera and light mounting considerations. Pictures of the test model should show location and distribution of pressure taps. Examples of documentation photos are shown in figure 2.

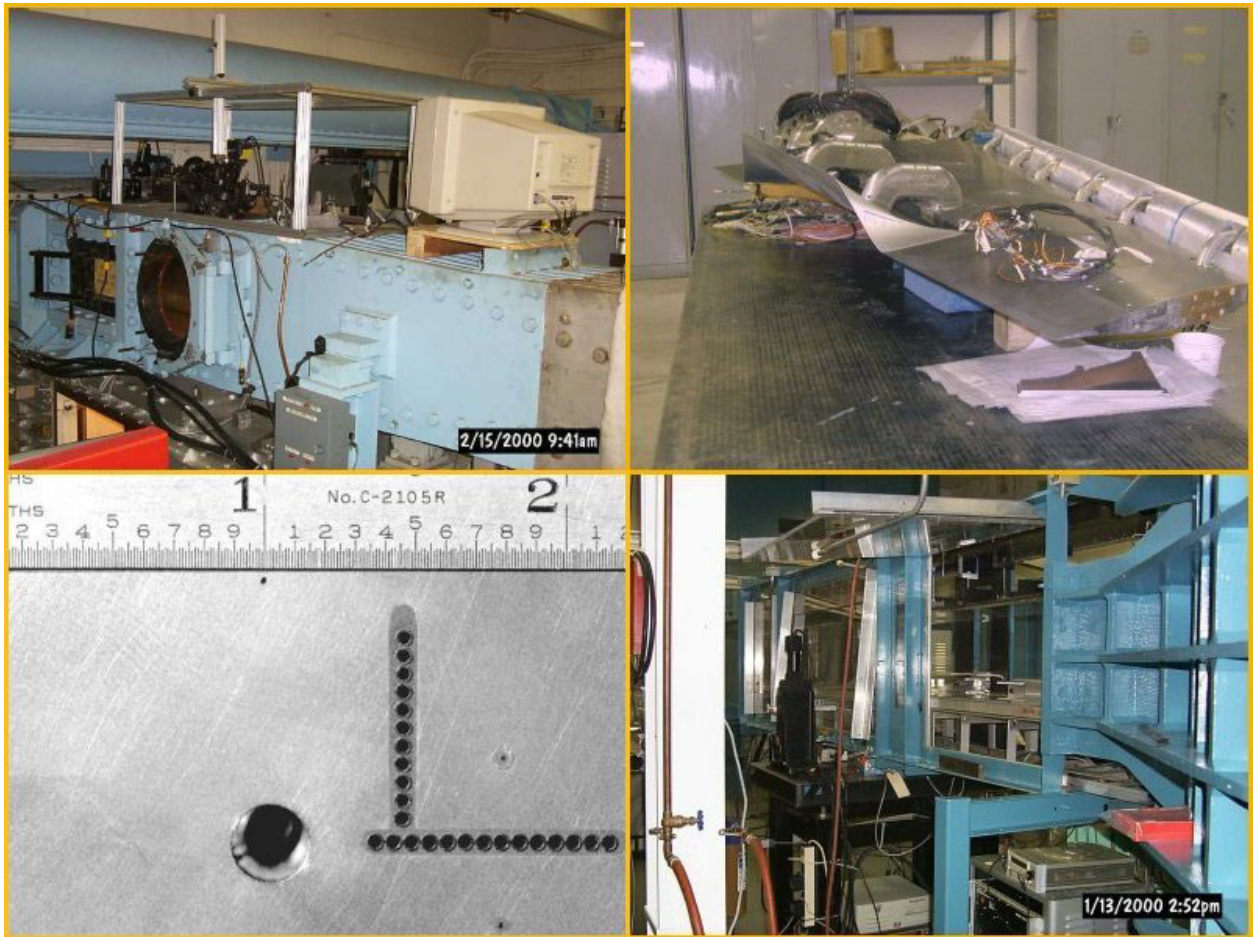


Figure 2. Examples of documentation photos (clockwise from top-left): 20-Inch Mach 6 Tunnel test section showing camera and light mounting hardware; trapezoidal wing model; Low Turbulence Tunnel test section; close-up of pressure taps on test model.

Test Support Request Form

Documentation for a given test should be initiated with the Test Support Request Form that will contain basic information about the test. This information is usually obtained at the first meeting with the customer. The information from this form will be used to select the appropriate field system components. A blank Test Support Request Form is given in Appendix A.

Test Requirements

A Test Requirements document will include a more formal outline of the test requirements based on the Test Support Request Form. Information for the test requirements is developed over several meetings or telephone conversations with the customer. The objectives of the test are also given. A Test Requirements example is given in Appendix B.

Test Plan

The Test Plan outlines in detail the steps necessary to fulfill the test requirements. It should include a schedule and personnel assigned for each task of the test. An example Test Plan is given in Appendix C.

Test Log

For each field test there should be a test log. A log can be kept either electronically or in a bound notebook, or both. The preferred method is the electronic notebook. The log should be commenced on or prior to the first day of on-site activity. It should include 'who did what when' and should detail problems encountered and how they were or might be solved. The test log is especially useful to keep personnel on each shift of a multi-shift test apprised of what occurs on other shifts. An example of a test log is given in Appendix D.

Field Test Procedures

Field tests are grouped into five phases: model painting, model measurement, equipment set-up, image acquisition, and image processing.

Model Painting

The procedure used to apply pressure sensitive paint depends on the particular paint formulation used in a test. Procedures for several paint formulations are given in Appendix E. Generally, the painter should be skilled in the application of PSP or TSP and always adhere to proper safety regulations for the facility and chemical handling.

Model Measurement

After the model has been painted it is necessary to apply registration targets to the finished surfaces at various points on the model. Targets are applied with a marker (Sharpie) and spaced on the model so as to provide at least 6 small (.1 to .5 inches diameter depending on model size and camera resolution) round dots in the camera image. The objective is to have each target represented by a three by three array of pixels in the acquired image. Targets are necessary so that wind-off and wind-on images may be accurately ratioed. After the targets are applied, their three-dimensional locations must be measured with a coordinate measurement system. The field system at NASA Langley Research Center uses a FARO Arm measurement system that has an eight-foot diameter reach and an accuracy of 0.001 inches. The procedure for using the FARO Arm is given in Appendix F.

Equipment Set-Up

Equipment set-up will consist of installing lights and camera(s) and adjusting the camera(s). The procedures for each are given in the following sections.

Light Installation

The number of lights needed will vary according to the type of lights used, the distance from the model, and the model geometry. The light most frequently used is the ELC-250 which produces 250 watts. New, more stable LED lights are also used. In general, the more lights the better. In a test at 20-Inch Mach 6 two ELC-250's were used about a foot away from the model. In tests at 16-Foot TT, twelve of these lights are used eight feet from the model. Lights should be aligned so as to distribute the light as uniformly as possible and to minimize the effects of shadows and reflections on the model. A plot of the variation in spatial uniformity of two light sources is shown in figure 3. This shows intensity versus angle for ELC-250 and in-house developed LED UV lamps. The ELC's have a more uniform distribution over a wide area while the LED's produce more intense output in the 20-degree center of their footprint. In addition, the lights should be securely mounted to stationary structures in order to eliminate movement from vibrations or other means.

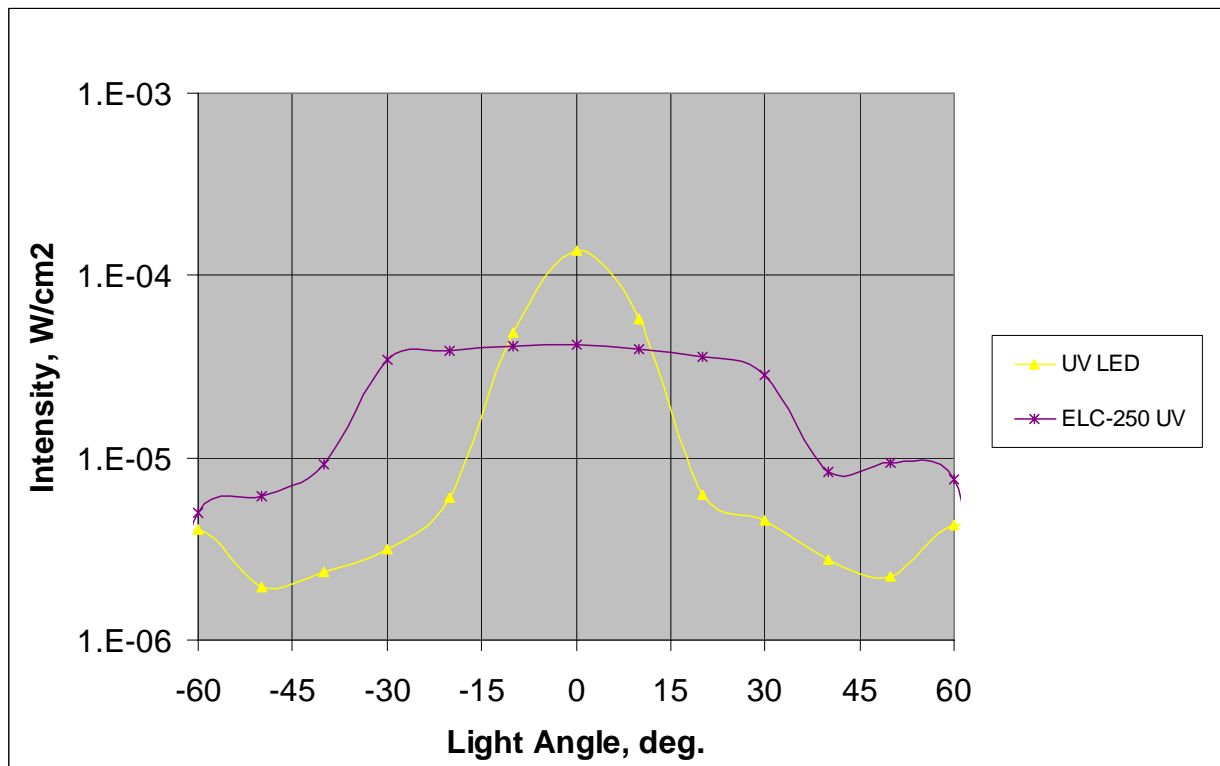


Figure 3. Spatial variation of illumination sources.

Camera Installation

The camera(s) should be positioned so that the model can be imaged throughout its full range of motion for the test without having to move the camera. A suitable selection of lenses will produce a reasonable image resolution while allowing for model motion. It is critical that each camera be securely mounted to minimize camera motion.

Camera Adjustment

Camera adjustment consists of focus, aperture, and exposure. Initial focus can be done with the unpainted model, without camera filters, in natural light. All final adjustments must be done with a painted model, appropriate camera filters, and all lights turned on. This is normally a two-person operation. One person makes the adjustment at the camera while another person monitors successive images in the control room. The two communicate by intercom or by radio when not within hearing range of each other.

The camera aperture should be as small as possible to maximize the depth of field so that the model stays in focus as angle-of attack is changed. However, it should not be so small as to require a long exposure time. An ideal aperture/exposure combination would be such that the model is always in focus with an exposure time of one second or less.

After focus and aperture adjustments are completed the lens/filter assembly should be securely taped in place so that the focus is not lost under vibration.

Final exposure time adjustment should be such that an intensity of two-thirds of the full range of the camera is produced in the image. For a 14-bit camera a maximum intensity would be about 12,000 (out of a total intensity of about 16,000). For a 16-bit camera a maximum intensity would be about 40,000. This is critical to prevent image saturation.

As testing proceeds it may be necessary to make adjustments to the exposure time. Usually the time will need to be increased because of photodegradation of the paint, especially if testing proceeds over several days. All of the particulars of camera settings and exposure times must always be recorded in the Test Log.

Image Acquisition

Image acquisition is accomplished by means of software supplied by the manufacturer of the particular camera used. Reference should be made to the manufacturer's instructions for proper operation.

Image Processing

All processing of images is carried out with 'GreenBoot' software. The program is widely used in government facilities for reducing and presenting PSP and TSP images. The procedure for using GreenBoot is given in Appendix H. An example of a processed PSP image is shown in figure 4.

All data will be given to the customer usually in the form of removable media. The data will include raw data images, geometry files, processed image data, and any photographs made of the set-up, etc. Each test may also be documented on a website available to the customer.

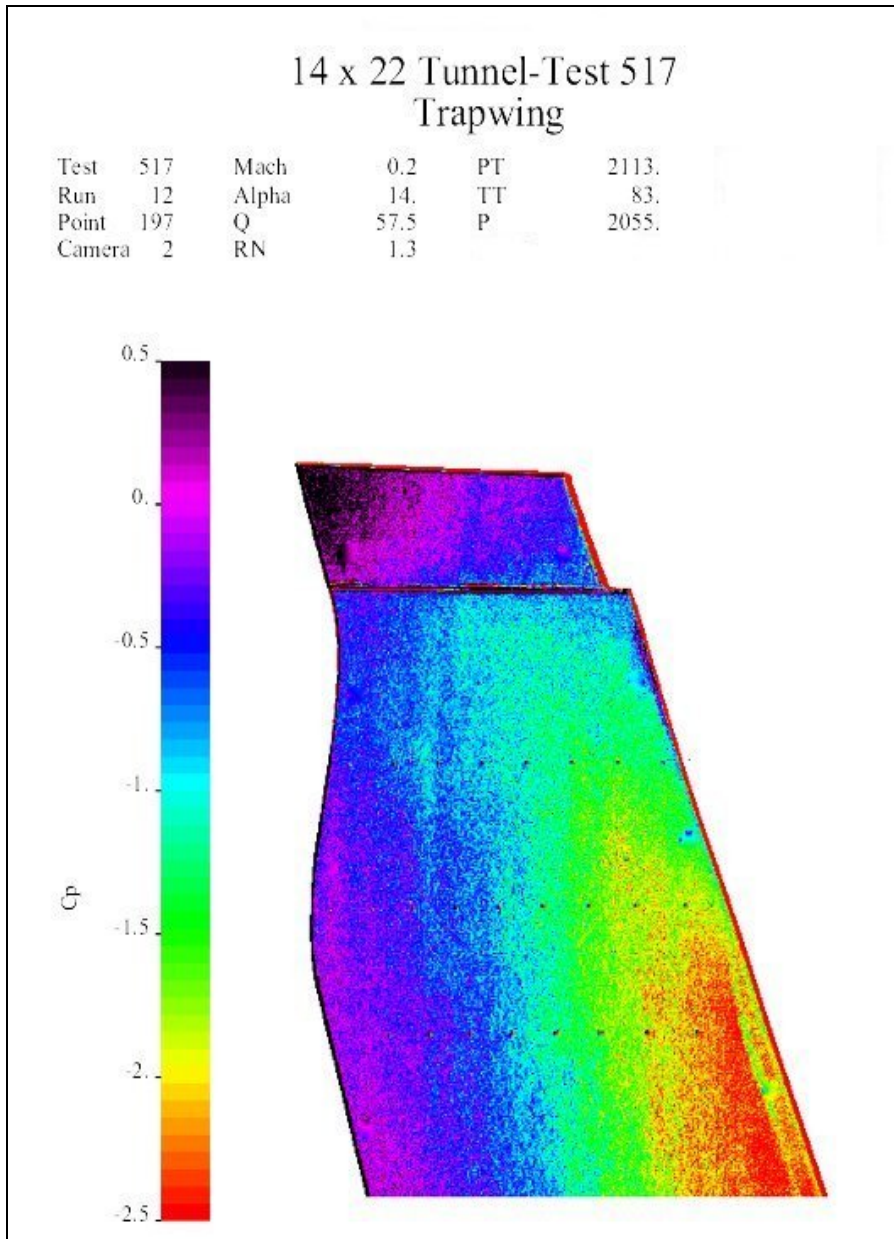


Figure 4. Processed PSP image.

Summary

The Pressure and Temperature Sensitive Paint Field System will continue evolving to meet the needs of Langley's aerodynamicists who require global surface pressure and temperature data on wind tunnel models under various test conditions. New paint formulations are being developed that will allow testing over greater ranges of pressures and temperatures. New illumination and imaging technologies are achieving greater stabilities and accuracies. The PSP/TSP Field System will be accordingly enhanced to maintain its state-of-the-art capabilities.

Appendix A
Test Support Request Form

TEST SUPPORT REQUEST FORM

NAME OF TEST	
NAME OF PROGRAM, LABOR CODE	
TEST DURATION & DATE	
WIND TUNNEL	
REQUESTER	
PHONE	
E-MAIL ADDRESS	
MODEL DESCRIPTION	
CONFIGURATIONS	
MACH NUMBER	
REYNOLDS NUMBER	
ANGLE-OF-ATTACK	
BETA	
TEMPERATURE	
PRESSURE	
OTHER CONDITIONS	
SHIFTS / HOURS	
PSP OR TSP	
CHEMISTRY	
LIGHTING RQMNTS.	
LIGHT FILTER	
CAMERA RQMNTS.	
CAMERA FILTERS	
PRESSURE TAPS	

Appendix B

Test Requirements

[TEST REQUIREMENTS EXAMPLE]

20-Inch Mach 6 Step Model Test Requirements

This document details specific requirements for using PSP to measure surface pressures on a rearward-step model in the 20-Inch Mach 6 Tunnel.

Objective

The objective of the test will be to use pressure sensitive paints to obtain quantitative surface pressures on a flat plate rearward-step model. This test is part of a larger test to study surface flows in gaps of metallic Thermal Protection Systems for hypersonic flight.

Customer: Dr. Robert Nowak of the Aerothermodynamics Branch.

Requirements

1. Prepare, prime, paint, cure, and register model with FEM inside test section at 1.7-2.7 mil thickness and 10 microinches or better roughness.
2. Verify lights are working and model surface is illuminated uniformly.
3. Verify light activation from control room.
4. Acquire image for each 10-second model residence test point.
5. Provide to customer C_p image for each test point.

[END OF EXAMPLE]

Appendix C

Test Plan

[TEST PLAN EXAMPLE]

20-Inch Mach 6 Step Model PSP Test Plan

OBJECTIVE: To use pressure sensitive paints to obtain quantitative surface pressures on a flat plate rearward-step model. This test is part of a larger test to study surface flows in gaps of metallic thermal protection systems for hypersonic flight.

Model: flat plate rearward-step model
Tunnel Entry: 2 weeks in May 2001
PSP equipment: CH250, 1-2 UV lamps, PC, SGI
Paint: SC-FEM, TSP
Model residence time: ~20 seconds
Model surface pressure: 0.04-2.7 psia
Number of pressure ports: 15

Tunnel contacts: Bob Nowak, Johnny Ellis

PERSONNEL:

Bob Nowak—Chief Investigator
Johnny Ellis—Tunnel Test Technician
Jerry Fitzgerald—Model Technician
Clifford Obara—PSP Team Leader
Danny Sprinkle—Lead PSP Test Engineer, image acquisition
Tahani Amer—Lead Image Processor
Cecil Burkett—PSP Technician, image acquisition
Dan Pritchard—PSP Technician, image acquisition
Troy Carmine—PSP Technician, camera & lights mounting, model painting, image acquisition
Brad Leighty—PSP Technician, camera & lights mounting (as needed)

SCHEDULE:

Day 1 & 2: Transport PSP system components to tunnel in Building 1247. Install PSP system components. Paint model with TSP and apply registration targets. Measure paint thickness and roughness.

Day 3: Check out system, make final alignments, light settings, etc.

Day 4-5: Acquire TSP images. Process image data.

Day 5: Strip and clean model. Paint model with SC-FEM and apply registration targets.

Day 6-10: Acquire PSP images. Process image data.

Roles and Responsibilities

Operation	Responsible Person(s)	Comments
Model installation	Johnny Ellis Jerry Fitzgerald	
Pressure instrumentation	Johnny Ellis	
Image acquisition components installation (PC, camera cables, etc.)	Troy Carmine Dan Pritchard Danny Sprinkle	
Camera & lights mounted	Troy Carmine	
Model prep	Troy Carmine	
Model painted	Troy Carmine	
Model registered	Troy Carmine Dan Pritchard	
Paint thickness & roughness measured	Troy Carmine Dan Pritchard	
Lamps working and controllable from control room	Cecil Burkett Troy Carmine Dan Pritchard	
Camera aperture & exposure time adjusted	Danny Sprinkle	
Raw images acquired	Danny Sprinkle Troy Carmine Cecil Burkett Dan Pritchard	
Tunnel test parameter data supplied to PSP team	Johnny Ellis	
All raw images backed-up on CD	Cecil Burkett Troy Carmine	
Images processed to render Cp data	Tahani Amer	
Test logbook kept	Danny Sprinkle	

[END OF EXAMPLE]

Appendix D

Test Log

[TEST LOG EXAMPLE]

15-Inch Low Turbulence Tunnel PSP Test Log

Test Plan

Jan. 18-28, 2000

Objective: To produce a global surface pressure map of a ramp model.
J.O.: R24542

Model: ramp
PSP equipment: CH350, 2-4 ELC-250's
Paint: FEM PSP

Tunnel contact: Scott Anders

PSP Personnel:

Danny Sprinkle— image acquisition/processing
Tahani Amer—image processing
Cecil Burkett—image acquisition/processing
Troy Carmine—model painting
Brad Leighty—lights and camera mounting

Schedule:

Jan 18-19 Transport PSP system components to 15-Inch Low-Turbulence Tunnel in Building 1247B.
Install PSP system.

Jan 19 Remove ramp model and transport to paint facility. Paint ramp model.

Jan 20 Install ramp model. Check out system, make final alignments, light settings, etc.

Jan 21 Acquire run images. Process run images.

If we get a good ratioed image we'll proceed with the following:

Jan 24-28 Acquire customer data. Process customer data

LOG

Tuesday Jan 18: All equipment is in place before 9 am (Brad was in at 5 am). CH350 camera and two ELC250 lights are mounted. PC is in place and connected to camera system. Several test shots were taken to verify operation. The ramp model was taken out and is now in B.1230. Troy says the model will be painted by tomorrow (Wednesday) afternoon. We can then take it over and give it to tunnel personnel to install Thursday morning. Scott Anders says it should take less than an hour to install the model. Brad estimates 2-3 hours to adjust the lights and camera settings. *Perhaps* we'll be able to crank up the tunnel Thursday. Certainly Friday.

Wednesday Jan 19: Troy spent the day preparing, priming, painting, and curing the model. He pronounced it ready for tunnel installation. Tomorrow we'll deliver it to the tunnel.

Thursday Jan 20: Center closed until noon because of snow. Delivered model 12:35 pm. Calibrated thickness gauge while model was being installed. Model installation completed by 2 pm. 18 mm lens used. 6 registration marks applied and field of view adjusted to show leading (top) edge of model. All images will show flow going from top to bottom. Registration marks in place 2:22. Test section closed 2:28. Side mounted lights gave uneven illumination. Both lights were remounted on the top.

Friday Jan 21: Ran tunnel with 1 ELC-250 light mounted at top. All images 4 seconds exposure time @ F11 aperture setting. Got good images but no decent ratio. Ran again after lunch after applying 6 vortex generators along leading edge. Ran tunnel at full throttle which produced 127 ft/sec. Took 20 darks, 20 wind offs, 20 darks, 20 wind ons. Images have highest pixel counts about 52k. Transferred all 80 images to CD.

Monday Jan 24: Gave images to Tahani to run on GreenBoot. Results show no pressure gradient. Checked response of paint by flowing nitrogen across model. These nitrogen images clearly show robust response.

Tuesday Feb 1: Ran again with 2 newly acquired green LED lamps instead of ELC-250's. Acquired 10-second images @F11: 10 wind-offs, 10 wind-ons, and 20 darks. Highest pixel counts about 30k. Neal Watkins took a CD of the images and ratioed them, correcting for darks and taking averages (see 4.2.6). There is definitely a trend, albeit noisy. There is also an artifact to be seen in the images that Jeff Jordan ascribes to the CH-350. Neal and Jeff recommend doing another tunnel run taking the following measures: Use the CH-250 instead of the 350; acquire 100 wind-offs, 100 wind-ons, and 100 darks. Cecil will locate a long cable for the camera. He will also write a script file that will be used to take these multiple images automatically.

Wednesday Feb 2: Replaced the CH-350 with the CH-250 (14-bit). Ran tunnel again at full speed. Scott Anders acquired pressure data. Took 100 wind-offs, 100 wind-ons at 10 seconds and F5.6, and 100 darks. Highest pixel counts about 6500. Gave CD of images to Neal Watkins for quick analysis.

Thursday Feb 3: Neal analyzed data and produced ratioed images (see 4.2.7). These images are similar to last images but less noise. There also appear to be imperfections that are thought to be paint related. Neal and Jeff recommend a new coating of PSP and running again with the same setup. Troy will paint and we may be able to run tomorrow.

Friday Feb 4: The model was painted and cured by 7:30 PM yesterday and was delivered to tunnel technicians today by 9:30 AM. The model installation was complete by 1 PM. Tunnel technicians installed thermocouple in tunnel. Based on images from the 2 previous runs it was subsequently determined by measurements that the tunnel ceiling was an eighth of an inch higher on one side. The ceiling was then leveled before this day's run. Ran the tunnel for 20 minutes to heat it up. Took 100 darks at this time. Tunnel went from 67 to 75.5 degrees F. Turned tunnel off and took 100 wind-offs. Turned tunnel back on and took 100 wind-ons. Turned tunnel off and took 100 wind-offs. Saved all images on hard drive and CD. Delivered CD to Neal Watkins shortly after 4 PM.

Tuesday Feb 5: Neal presented the latest results at the PSP meeting. Results show pressure gradient across the model. It was decided to bring the model back to 1230 to measure the registration marks with the FARO Arm in order to proceed with GreenBoot analysis. Scott Anders will need the model until Monday morning to try out different vortex generator configurations in the tunnel. We will retrieve the model from the tunnel Monday the 14th.

Monday Feb 14: Scott Anders reports that he was unable to get a desired pressure response on the model using various combinations/arrangements of vortex generators and is therefore not interested in pursuing PSP tests on this particular model. He may want us to run PSP on another model (yet to be fabricated) some time in the future. We will perform FARO Arm measurements on the model and give all pertinent data to Tahani to run through GreenBoot. Retrieved the model from tunnel. We also retrieved the CH350 and hardware/PC associated with the CH350. Still at the tunnel are the CH250 and hardware/PC associated with the CH250, the 2 green LED lights, and 2 ELC 250's.

Thursday Feb 17: Gave Tahani a CD of the 400 images of 4-2-00 and a floppy of the pressure data. Cliff will take model to photo lab tomorrow to get photos of pressure ports. Then Troy will measure model with FARO Arm.

[END OF EXAMPLE]

Appendix E

Procedures for the Preparation and Application of Pressure and Temperature Sensitive Paints

General Procedures and Precautions

- When working with paints and solvents always work in a well-ventilated area. Avoid breathing solvent vapors. If ventilation is not adequate use a fresh air breathing apparatus.
- Wear Eye protection.
- Wear nitrile gloves when working with paint and solvents. This is important for both protection of hands and avoiding fingerprint contamination of the clean model surface.
- Dust can ruin an otherwise good paint job. Work in a clean environment and always wipe surfaces to be painted with a tack cloth.
- When cleaning, sanding, or painting a model with taps, always maintain an air purge through the taps, cover, or close the taps to prevent clogging.
- Final paint thickness should be less than 0.003 inches.
- Final paint roughness measurement should be less than 10 microinches for 2-part FEM and less than 35 microinches for Single Coat FEM. Sanding of Single Coat FEM to a smoother finish will depend on the specific test requirement.
- Use the lowest possible air pressure setting on the paint gun that will apply the paint with an acceptable finish.
- Always keep the painted model covered to avoid photo degradation of the luminophore in the paint and contamination of the painted surface.
- Spray a test coupon for calibration at the same time the model is painted.
- **NEVER** touch, wipe or clean the painted surface without first consulting the person who applied the paint.

Procedure for Preparing and Applying Prime' N Seal Primer

1. Thoroughly shake or stir the DuPont white primer-sealer (Prime'N Seal).
2. Transfer half the total volume of paint required from the can to a smaller container for mixing with the activator.
3. Measure an equal amount of DuPont Prime'N Seal overall activator and add it to the white primer-sealer. Mix thoroughly and strain. The mixture is usable for 96 hours after activation.

4. Apply an air purge to the model taps to prevent particles or paint spray from entering the taps. Adjust the airflow such that no cratering occurs around the taps.
5. Wear nitrile rubber gloves.
6. Clean the surface of the model to remove all traces of oil, grease, and surface impurities with DuPont lacquer thinner. Once the model is clean it should be handled with gloves on.
7. Mask off the model areas that will not be painted. Use 3M Scotch Brand 218 MQA striping tape.
8. Lightly wipe the exposed surface with lacquer thinner to remove any fingerprints or other contamination.
9. Wipe the surface with a tack cloth just prior to spraying to remove any dust.
10. Adjust a Paasche airbrush to maintain 32 psi while on.
11. Spray the entire surface with a light coat of primer and allow it to dry for about 30 seconds.
12. Continue spraying until a smooth, uniform, glossy coating is achieved, and the bare model surface cannot be seen through the primer.
13. Clean the spray gun with DuPont lacquer thinner.
14. If heat lamps are to be applied allow the paint to cure for 20 minutes before applying heat.
15. Remove the masking before curing.
16. Allow the primer to air cure 12 hours or cure for 2 hours at 60° C or 1.5 hour at 65° C (not counting the time it takes to reach the cure temperature).

Procedure for Preparation and Application of FEM Pressure Sensitive Paint

Thoroughly clean the surface of the model to remove all traces of oil, grease, and dust. Spray the surface with Prime'N Seal, using the 2605S Overall Activator. Cure the primer for 1.5 hour at 65° C.

FEM paint mixture (for approx. 2 oz):

¹ polytrifluorethyl-co-isobutyl methacrylate 50% in toluene (TFEM/IBM)_____	2.8 g
solvent 3602S _____	48.4 g
solvent 3979S _____	4.8 g
PtT(PFP)P (600 ppm) _____	33.6 mg

1. Tare a jar or glass container of the appropriate size.

2. Weigh the TFEM/IBM in toluene into the tared container and record the weight
3. Retare the container and TFEM/IBM to bring the balance reading to zero.
4. Weigh the 3602S into the retared container and record the weight
5. Retare the container, TFEM/IBM, and solvent mixture to bring the balance reading to zero.
6. Weigh the 3979S into the retared container and record the weight.

Dissolve the TFEM/IBM in the solvents by stirring or vigorous shaking of the sealed container.

Tare a small glass vial on the analytical balance (0.0001 mg sensitivity). Weigh the appropriate amount of PtT(PFP)P into the vial. Completely dissolve the PtT(PFP)P in a small amount (about 1 ml) of toluene and add the solution to the TFEM/IBM/solvent mixture and mix thoroughly.

After initiating an air purge through the pressure taps, wet sand the cured Prime'N Seal with 2000 grit paper to a roughness of 5 microinches, as measured with the Mitutoyo Surf test 211. Wipe the surface with a tack cloth and spray to a uniform, smooth pink color. Allow the paint to cure at room temperature for about 20 minutes before heating to 60° C for one hour.

Notes on the Painting Process:

- Test spray at 32 p.s.i., when using a Paasche air gun, to see if there are strings in the spray stream. If strings exist add thinner one capful at a time until the strings disappear, then add 4 -6 more caps of thinner per 8 oz of paint.
- Spray a thin coat initially. After this is tacky (only takes a few seconds to become tacky), apply a thicker coat.

Application of FEM Pressure Sensitive Paint on Self- Etching Primer and Krylon Primer

Thoroughly clean the surface of the model to remove all traces of oil, grease, and dust. Apply an air purge to the taps and then apply a light coating of Sherwin Williams 988 Self Etching Primer and allow it to dry for 30 minutes (See directions on the back of the can.). After the 988 has dried apply sufficient white base coat (white Prime'N Seal, white KRYLON, FEM primer, etc.) to give a smooth finish and allow to cure completely.

FEM paint mixture (for approx. 2 oz):

¹ polytrifluorethyl-co-isobutyl methacrylate (TFEM/IBM) 50% in toluene _____	10.0 g
solvent 3602S _____	50.0 g
solvent 3979S _____	4.06 g

PtT(PFP)P (0.7 % of resin) _____ 35.0 mg

Dissolve the TFEM/IBM in the solvents. Dissolve the PtT(PFP)P in about 5 ml of toluene and stir until dissolved. Add this solution to the solvent/polymer mixture and stir.

Dust or other blemishes may be sanded from the base coat finish with 600 grit paper if necessary. Wipe the surface with a tack cloth and spray the FEM PSP to a uniform, smooth, pink color. Clean the spray gun with DuPont lacquer thinner. Allow the paint to cure at room temperature for about 20 minutes before heating to 60° C for one hour.

Preparation of FEM White Primer

Thoroughly clean the surface of the model to remove all traces of oil, grease, and dust.

FEM paint mixture (for approx. 2 oz):

polytrifluorethyl-co-isobutyl methacrylate 50% in toluene (TFEM/IBM)_____	10.0 g
solvent 3602S _____	50.0 g
solvent 3979S _____	4.0 g
TiO ₂ pigment - Dupont 706 _____	3.3 g
Anti-Terra-U (1 % of TiO ₂ wt.) _____	0.04 g
Triton X-100 (1 % of TiO ₂ wt.) _____	0.04 g

1. Tare the vessel of appropriate size in which the paint is to be blended.
2. Weigh the TFEM/IBM into the tared container and record the weight
3. Tare a separate container for the solvents.
4. Weigh the 3602S into the tared solvent container and record the weight
5. Retare the solvent container and add the appropriate weight of 3979S to the solvent mixture.
6. Tare a separate container for the pigment. Weigh out the appropriate amount of TiO₂.
7. Tare a separate container for the Anti-Terra-U (dispersant) and Triton X-100. Weigh the appropriate amounts of Anti-Terra-U and retare the container and weigh the appropriate amount of Triton X-100 into the same container.
8. Dissolve the Anti-Terra-U and Triton X-100 in a small amount of solvent from the weighed solvent mixture (about 5 ml).

9. Add the Anti-Terra/ Triton/solvent mixture to the container with the polymer.
10. Add the TiO_2 to the container with the polymer and dispersant blend.
11. Stir the mixture until the TiO_2 is uniformly dispersed. The blend should be fairly viscous.
12. Attach the appropriate size Cowles blade to the blender and position the polymer container so that the Cowles blade is submerged in the polymer/ TiO_2 /dispersant mixture.
13. Start the blender. Adjust the position of the blade to achieve vortex. The speed should be about 600 rpm. This stage of the mixing process is called the grind.
14. Grind for 30 minutes, occasionally adding solvent from the weighed solvent mixture to compensate for evaporation or to adjust the viscosity of the blend.
15. At the end of 30 minutes add the rest of the weighed solvent mixture, and blend for 5 minutes.
16. Fold a paint filter so that it will fit into the container into which the solvent mixture was weighed.
17. Filter the blended paint mixture into the solvent container.
18. After initiating an air purge through the pressure taps, wipe the surface with a tack cloth and spray to a uniform, smooth pink color. Allow the paint to cure at room temperature for about 20 minutes before heating to 60°C for about 30 minutes. If necessary, wet sand the cured Single Coat FEM PSP with 2000 grit paper to a roughness of 10 microinches, as measured with the Mitutoyo Surf test 211.

Notes on the Painting Process:

- Spray a thin coat initially. After this is tacky (only takes a few seconds to become tacky), apply a thicker coat.
- Spray a test coupon for calibration at the same time the model is painted.

Application of FEM Single Coat Pressure Sensitive Paint on Self-Etching Primer

Follow the procedures given for FEM application on 988 but the white coat is not needed.

Procedure of the Preparation and Application of FEM Single Coat Pressure Sensitive Paint

Thoroughly clean the surface of the model to remove all traces of oil, grease, and dust.

FEM paint mixture (for approx. 2 oz):

polytrifluorethyl-co-isobutyl methacrylate 50% in toluene (TFEM/IBM)_____	10.0 g
solvent 3602S _____	50.0 g
solvent 3979S _____	4.0 g
TiO ₂ pigment - Dupont 706 _____	3.3 g
Anti-Terra-U (1 % of TiO ₂ wt.) _____	0.04 g
Triton X-100 (1 % of TiO ₂ wt.) _____	0.04 g
PfT(PFP)P (0.7 % of resin) _____	35.0 mg

1. Tare the vessel of appropriate size in which the paint is to be blended.
2. Weigh the TFEM/IBM into the tared container and record the weight
3. Tare a separate container for the solvents.
4. Weigh the 3602S into the tared solvent container and record the weight
5. Retare the solvent container and add the appropriate weight of 3979S to the solvent mixture.
6. Tare a separate container for the pigment. Weigh out the appropriate amount of TiO₂.
7. Tare a separate container for the Anti-Terra-U (dispersant) and Triton X-100. Weigh the appropriate amounts of Anti-Terra-U and retare the container and weigh the appropriate amount of Triton X-100 into the same container.
8. Dissolve the Anti-Terra-U and Triton X-100 in a small amount of solvent from the weighed solvent mixture (Use about 5 ml).
9. Add the Anti-Terra/ Triton/solvent mixture to the container with the polymer.
10. Add the TiO₂ to the container with the polymer and dispersant blend.
11. Stir the mixture until the TiO₂ is uniformly dispersed. The blend should be fairly viscous.
12. Attach the appropriate size Cowles blade to the blender and position the polymer container so that the Cowles blade is submerged in the polymer/TiO₂/dispersant mixture.
13. Start the blender. Adjust the position of the blade to achieve vortex. The speed should be about 600 rpm. This stage of the mixing process is called the grind.
14. Grind for 30 minutes, occasionally adding solvent from the weighed solvent mixture to compensate for evaporation or to adjust the viscosity of the blend.
15. At the end of 30 minutes add the rest of the weighed solvent mixture, and blend for 5 minutes.

16. Fold a paint filter so that it will fit into the container into which the solvent mixture was weighed.
17. Filter the blended paint mixture into the solvent container.
18. Tare a small glass vial on the analytical balance (0.1 mg sensitivity). Weigh the appropriate amount (0.007 x 0.5 x wt. of resin/toluene mixture) of PtT(PFP)P into the vial. Completely dissolve the PtT(PFP)P in a small amount (about 1 ml) of toluene and add the solution to the blended paint and mix thoroughly. After initiating an air purge through the pressure taps, wipe the surface with a tack cloth and spray to a uniform, smooth pink color. Allow the paint to cure at room temperature for about 20 minutes before heating to 60° C for about 30 minutes. If necessary, wet sand the cured Single Coat FEM PSP with 2000 grit paper to a roughness of 10 microinches, as measured with the Mitutoyo Surftest 211.

Notes on the Painting Process:

- Spray a thin coat initially. After this is tacky (only takes a few seconds to become tacky), apply a thicker coat.
- Spray a test coupon for calibration at the same time the model is painted.

Appendix F

Coordinate Measurement Procedure

- 1) Set up all FARO Arm equipment:
 - Laptop
 - Attach 0.125" ball tip to FARO Arm
 - Turn all equipment on
 - 2) Arrange FARO Arm tripod so all areas of interest on the model can be reached with the tip.
 - 3) Secure tripod feet to floor using tape to prevent tripod movement during use.
 - 4) Exercise all joints on arm through their limits. Observe *RED* lights on the control panel. As each light goes off, move to next joint. Light number *TWO* will stay on until that arm joint has been moved off its "rest" stop.
 - 5) Set up probe in the CALIPER 3D software to reflect which tip is being used as follows:
 - a) Click on Settings menu tab.
 - b) Click on Probes.
 - c) Click on Ball Probe.
 - d) Enter 0.125 in the DIAMETER window.
 - e) Click OK.
 - 6) Calibrate the arm and take target data as follows:
 - a) Click on Alignments menu tab.
 - b) Select Datum Point.
 - c) Select LOAD.
 - d) Select the file for the RIGHT or LEFT wing.
 - e) Click OK.
 - f) Click on Digitize XYZ.
 - Datum Point Alignment window will appear
 - g) The menu should now have "Digitize the point at position #1" in the center of the Window.
 - If this is displayed, the arm is ready to define its coordinate system.*
 - h) Place the arm BALL on the first reference point as shown on the wing diagram.
- Note: Do not just count back the number or ports shown on the diagram or seen on the model as they do not reflect exactly what is there. Example: On the wingtip the port labeled "3" is only the second hole seen on the model if you count holes. Pay close attention to the labeling of the ports on the diagram.*
- i) Use the FRONT (bottom) and BACK (top) buttons (either side of head) to take data points.
 - j) Forty (40) to fifty (50) points are taken at each reference point to get an average to compensate for vibration during the measurement. To capture a point push the button closest to the probe (front button) once and then farthest from the point (back button) to lock it in. A *bad point* can

be erased before hitting the back button just by hitting the front button again. The delete button on the screen can be used if the back button was already hit.

- k) After taking 40-50 readings at this point, hit the back button twice *but not too quickly* to advance to the next reference point. The screen will display “ Digitize the point at position #2 “ when it is ready.
- l) Repeat # j for the second and third points.
- m) After the third reference point, arm is ready to take the target locations. If it displays an error message, then repeat the process starting from #4.
- n) Measure all target locations on the wing and save the file. e.g: F18LW818.
- o) Repeat the process for the other wing starting at Step 6.

Appendix G

GreenBoot Procedures

Introduction

GreenBoot (GB) is a software product designed to provide an easy way to process images of wind tunnel models coated with pressure and temperature sensitive paint (PSP/TSP). The goal of the image processing is to recover pressure data over the entire surface of the model to which PSP/TSP has been applied. GreenBoot is intended to be used in a production wind tunnel environment for rapid processing. GreenBoot is designed to simplify the data reduction process, be able to handle many different data reduction techniques, and is easy to accommodate new algorithms and procedures. However, GreenBoot is not designed to control data acquisition or run in real time processing. Several authors have written GreenBoot: Dexter Hermstad, Tom Kihlken, Mike Benne, John Donovan, and James Bell.

Hardware Requirements

Silicon Graphics Indigos are used for GreenBoot. This software will not run on Personal IRIS's, since these machines can't run OpenGL. It runs on a SGI Onyx, Sun machines, and DEC Alpha. GB requires a machine with at least 48 MB of memory and 75 MHz R4000 processor or better.

Software Requirements

In order to run GB properly, the following files are needed:

- *.gb GreenBoot configuration settings.
- *.ldb Image database containing a list of all known images.
- *.cam Camera setting database.
- *.tgts Targets and pressure taps locations.
- *.comp Geometry component database
- gb Executable for GreenBoot

GreenBoot Setup Checklist

Tap locations should be in the form:
ID XYZ in the same coordinate system as
the surface geometry. ID numbers must be
Unique. Taps must be listed in the same order
That they will appear in the WTD File output
by the wind tunnel data system

____ [long lead-time item] obtain Pressure
tap locations.

Must have model geometry for all
configurations in either PLOT3D
or CFL format. If PLOT3D must be
non-iblaned, multi-zone, unformatted or
binary formats

____ [Long lead-time item] Obtain model
surface geometry

On *Painter*, the test account is
XXXX, and the password is XXXXX

Type gb. GreenBoot should start.
The version number display in the shell
window should be 2.11a or greater.
(This version reads *.tif files)

Type df and verify that the user partition
is less than 50% full.

The easiest way to do set up is to copy
and rename files from a previous test.

Determine which grid files and zones are
used by each configuration.

Do this by opening and hand-editing
the image database

Be sure to start GreenBoot with the
current test database.
(Use the test file data folder)
(Eg: gb215 test101)

Open a geometry window and view
the images to see if the different
configurations are correctly displayed.

Select the file-print menu option in
the image window. Edit the print titles;
then cancel the print command.

_____ Log onto the test account

_____ Verify that GreenBoot is present

_____ Verify that disk space is available

_____ Create GreenBoot database files

_____ Update targets database with tap
locations and target locations.

_____ Update components database

_____ Create a fake 3D image for each
configuration.

_____ Define the cameras to be used in
the test in the camera database.

_____ Make an initial estimate of
which taps and targets will be seen
by which cameras.

_____ Start GreenBoot, Set the help
directory, base directory, printers
conditions names and grid files.

_____ Verify that the components
database is properly set up.

_____ Set up the default titles for the
print command.

_____ Quit GreenBoot, select Save to
ensure that the database files
are updated.

BASIC INSTRUCTIONS

START-TO-FINISH IMAGE PROCESSING

For further information and additional procedures, see Boeing's GreenBoot User's Guide, Version 2.10

Before beginning the following files must be created in a working folder: .gb, .tgts, .ldb, .cam, .comp

Legend:

◆ - Main Headings under each Window

□ - Subheading 1

▪ - Subheading 2

❖ - UNIX Shell action

1.1 In MAIN Window (shows all files)

◆ Select Database

□ Images

▪ Import

Change “.fit” to “.TIF”

Double click “image/” in path

Select 3 images (Wind ON, Wind OFF, Dark – use CTRL to select files needed)

▪ Click Import

▪ Close Import Images Window

Note: If there are a large number of images, use the “Make Idb” macro to get all data into the database at one time. If data is taken at low speed and several images are take for each run, run data must be averaged using the “average” macro

□ Edit camera, targets, components, or Run notes files if necessary

◆ Select Windows

□ New Image

▪ File

▪ Open

Set All Filters to Filename

Select (dark image) ***D.TIF from list

▪ Click OK

Scan image and verify proper values for pixel intensity (~130-140+)

▪ Close

1.2 In MAIN Window

◆ Select Windows

□ New Image

1.3 In IMAGE Window

- ◆ Select File
 - Open
 - Select (wind off image) ***F.TIF
 - Click OK
- ◆ Select File
 - Save as ***.off
 - (May also change “image” in file path to “process” if desired)
 - Click OK

1.4 In WIND OFF Image Window

- ◆ Select Process
 - Image Math
 - Subtract
 - Select ***D.TIF file (dark image) in list
 - Click OK

COMMENT: It is easier to see registration marks in grayscale

To do this:

- ◆ Select Display
 - Legend
 - Spectrum
 - Grey
 - Click OK

Also, to more accurately pick registration marks:

- ◆ Select Display
 - Magnify
 - Select desired Magnification lever (x5 – x 10)
- ◆ Click Regions
 - Point Picking (drag this window to the side)

Using predetermined grid for registration pattern, put CROSSHAIR on appropriate mark (magnify if desired, using Display...Magnify)

Press SpaceBar to set registration point

Continue to next point until all registration marks are registered

- Close Point Picking Window
- ◆ Select Display
 - Magnify
 - Normal Size
- ◆ Select Display

- ❑ Legend
 - Spectrum
 - Reverse Color Ramp
 - Click OK
 - ◆ Select Process
 - ❑ Apply Threshold
 - Background Value (or set Min value to some value near background levels – can undo last change in this window)
 - Click OK
 - ◆ Select File
 - ❑ Save
 - ◆ Select File
 - ❑ Save as ***.rat (**This is the RATIO Image**)
 - Click OK
- ❖ Minimize this Window if desired

1.5 In MAIN Window

- ◆ Select Windows
 - ❑ New Image

1.6 In IMAGE Window

- ◆ Select File
 - ❑ Open
 - Select ***.TIF file (wind on image) in list
 - Click OK
- ◆ Select File
 - ❑ Save as ***.on
 - (May also change “image” in file path to “process” if desired)
 - Click OK

1.7 In WIND ON Image Window

- ◆ Select Process
 - ❑ Image math
 - Subtract
 - Select ***.TIF file (dark image) in list
 - Click OK

COMMENT: It is easier to see registration marks in grayscale

To do this:

- ◆ Select Display
 - ❑ Legend
 - Spectrum
 - Grey
 - Click OK

Also, to more accurately pick registration marks:

- ◆ Select Display
 - Magnify
 - Select desired Magnification lever (x5 – x 10)

- ◆ Select Regions
 - Point Picking (drag this window to the side)

Using predetermined grid for registration pattern, put CROSSHAIR on appropriate mark (magnify if desired, using Display...Magnify)

Press SpaceBar to set registration point

Continue to next point until all registration marks are registered

- Close Point Picking Window

- ◆ Select File
 - Save

- ◆ Select File
 - Save as ***.warp (or wp) (**This is the WARP Image**)
 - Click OK

1.8 In WARP Image Window

- ◆ Select Process
 - Correlate
 - Second Order Polynomial
2nd order polynomial and projective are preferred for sting mounted models.
3rd order polynomial is preferred for semi-span model. Must have at least 10 control points (targets)

Select ***.rat from list of files (has wind OFF Run #)

- Click OK

View Equations and coefficients (In Main Window)
RMS Xerr & Yerr should be “small” (less than 0.5)

- ◆ Select Display
 - Magnify
 - Normal Size

- ◆ Select Process
 - Apply Threshold
 - Background Value (or set Min value to some value near background levels – can undo last change in this window)
 - Click OK

- ◆ Select File
 - Save

1.9 In RATIO Image Window

- ◆ Select Process
 - Image Math
 - Divide by
Select ***.warp (or wp) from list
 - Click OK
- ◆ Select File
 - Save as ***.cp (**This is the Cp Image**)
 - Click OK

1.10 In MAIN Window

- ◆ Select File
 - Setup
 - WTD Format
Insert filename for WTD Data file – e.g.: 00310306.wtd
(File format: xxxx(Run #)xxxx(point or Sequence #).wtd)
 - Click OK
- ❖ Open WTD file in another UNIX window to get run information
- ◆ Select Database
 - Images
 - Edit (Select ***.cp Image)

Enter Run # for Wind ON Image and Point or Seq. #

Enter Test #, Camera #, Exposure time, Mach, Alpha, ...
(Cp Image Window should display same entries made)

 - Close Edit Image Window
- ❖ Close UNIX window used to see the WTD file

1.11 Close WARP Image Window

.....we are done with it

1.12 In Cp Image Window

- ◆ Select 3D Process
 - Model Positions
 - Direct Linear Transformation
- ◆ Select Display
 - Click Show Regions (turn it OFF)
- ◆ Select Display

- ❑ Click Label Taps (turn it ON)

“May want to re-scale the colors and/or magnify the Display at this point to facilitate tap picking”

- ◆ Select 3D Process
 - ❑ Fit to Taps

1.13 In TAP CAL Window

View image to determine taps to use

Do not use taps that fall off of the model

Do not use taps that fall on Registration marks

Do not use taps that are on other “misleading” regions such as Shock Waves or tubing trenches

- ❑ Enter Tap Numbers used (e.g.: 1-20, 22, 24-30)
(Initially use all taps except predetermined unfavorable ones)
 - 1st Order Polynomial
 - 3x3, 5x5, etc
 - Calibrate (Leave TAP CAL window open)
- ❑ Click on Plot

View Tap vs Image file to help in evaluating and determining further taps to eliminate

1.14 In MAIN Window

View Equations and coefficients (Top Frame)

RMS difference should be “small” (less than 1.0)

*Re-enter taps to use and iterate the process until the calibration plot looks ‘good’. If you need to iterate **make sure you Close the Cal Plot Window before you calibrate each iteration.***

1.15 In TAP CAL Window

- ◆ Click on Plot button

1.16 In PLOT Window

(Click on plot axes to adjust scale and increment)

- ◆ Select File
 - ❑ Print
 - Destination PostScript File or Printer (for immediate printing)
 - Filename ***.plot.ps
(Substitute Wind on Pt # & Run #)
 - Click OK
- ◆ Select File
 - ❑ Close (Closes Plot Window)

1.17 Close TAP Cal Window

1.18 In Cp Image Window

- ◆ Select Display
 - ❑ Legend (Adjust scale and increments to optimize data)

(e.g. Max = 0.8, Min = -1.8, Inc = 0.2)

- ◆ Select Display
 - Click Label Taps (turn it OFF)
- ◆ Select Display
 - Magnify
 - Normal
- ◆ Select Regions (“If desired/needed/...”)
 - Patch
- ◆ Select File
 - Print
 - Destination PostScript File or Printer (for immediate printing)
 - Filename `***.image.ps`
Substitute Wind on Pt # & Run #
 - Click OK
- ◆ Select File
 - Save

❖ In a UNIX Shell window print both `***.image.ps` and `***.plot.ps` files on a color printer.

1.19 Close Cp Window

SHORT VERSION

START-TO-FINISH IMAGE PROCESSING

1. You must have created the following files (gb., tgts, .idb, .cam, .comp).
2. Open a wind off image and rename it *.off.
3. Subtract the dark image.
4. Pick the targets, using point picking under the Regions Menu, the same order as input target file (look at a diagram).
5. After all of the targets are picked, save the image as a ratio image (*.rat).
6. Open a wind on image and rename it *.on.
7. Subtract the dark image.
8. Pick the target points using point picking under the Regions Menu.
9. After all of the target points are picked save the image as a warp (*.wp).
10. Warp the *.off and *.on images by using correlate or register, located under the Process Menu of the Image Window.
 - 10.1 2nd order polynomial and projective are preferred for sting mounted models.
 - 10.1 3rd order polynomial is preferred for semi-span model.
11. Ratio the *.off and *.on images.
12. Resave the updated warp image.
13. Save the ratio image as a *.cp file. This is for the calibration process.
14. Under the main window, if data for the image has not been entered now is the time it must be done. (Test # and Run #, Point # and exposure time. The other tunnel conditions are optional.)
15. Before you go any further in GreenBoot two files must exist:
 - 15.1 The formatted wind tunnel data in the *.wtd file
 - 15.2 The unformatted copy of the WTD file in the *.dat file
16. Open *.cp file in the image window, under 3D Process Menu select Model Positions and then select Direct Linear Transformation.
17. Review equations and coefficients and if RSM difference is less than 1.0, proceed to do "Fit to Tap" which is under the 3D Process Menu.
18. Calibrate and then plot the pressure tap data.
19. Print the calibration plot and the image file.

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